FINAL REPORT

DESIGN STUDY FOR A TWO - COLOR BETA MEASUREMENT SYSTEM

TASK 5 OF CONTRACT NO. NAS8 - 34337

April, 1982

Report No. C - 81 - 01 - R. - 12

Applied Research, Inc.

P. O. Box 194 • Huntsville, Alabama 35804 • (205) 533 6987

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1. INTRODUCTION

The recent success of NASA/MSFC's Laser Doppler Velocimeter System which is designed to measure atmospheric backscatter, β, at 10.6 μm has generated an interest in determining the design of a two-color β measurement system. Applied Research, Inc. has undertaken an analytical system design effort, centered around existing β-system hardware, to result in a two-color β system. This effort is focused toward employing existing hardware to the maximum extent possible and does not explore the development of new signal processing electronics and/or mixing of two-color reflected signals on a common detector with two local oscillator frequencies. The results of this design study, including a ray trace analysis of a proposed two-color β-system design which employs the current system's beam expander, is given in the following sections of this report.

2. DESIGN CONSIDERATIONS

The decision to investigate two-color β-system designs that employ the maximum amount of existing MSFC hardware has been driven by consideration of other efforts which are more extensive and will explore multi-color β -system designs using new and to be purchased system hardware. The design to be derived from this study was not constrained to fit inside a pre-determined small volume emvelope or weight limit. This design effort considered several two-color system designs which ultimately result in two design options:

- A beam splitter combined two-color system (BSCTCS) which results in a common focal volume for the two transmitted beams.
- A two beam directing insertion mirror system (TBDIMS) which uses a common beam expander and focuses the two transmitted beams at approximately the same spatial location.

The BSCTCS was analyzed for two unique designs. One design which employed a 50% beam splitter as the beam combining component (for λ_1 and λ_2) on the transmit leg of the system was analyzed and found to have relatively low performance potential when compared to the other designs.

The other design which was considered employed a dichroic beam splitter as the beam combining component. This design was analyzed and found to have relatively higher potential for performance than the 50% beam splitter design. Other considerations employed a dichroic beam splitter in the return leg to separate reflected signals (λ_1' and λ_2') such that they could be combined with separate LOs and heterodyned on separate detectors. These designs are more fully discussed in Section 3.1, Design Analysis of the Beam Splitter Combined Two-Color β-Systems.

The second design, Two-Beam Directing Insertion Mirror System, (TBDIMS) was analyzed and found to have a very good system performance potential relative to the existing single-color β-systems. This second design was chosen for further system design analysis because it can potentially employ the existing β-system's interferometer, laser transmitter, beam expander, detector, and signal processing. This design will require the use of an additional signal processor (or time-sharing with the current signal processor), laser of wavelength λ_2, detector, interferometer and a

folding/beam directing flat mirror for beam insertion of the second color onto the existing beam expanding secondary. This system's design will be such that the spatial relationship of the two focal volumes will be known for various focal ranges and such that statistical correlation of $\beta(\pi)$ may be made for the two-colors whether employed in the single particle mode or the volume mode.

The TBDIMS design obviously employs more hardware and thus has larger volume and weight characteristics than the BSCTCS design. However, from the design analysis which predicts system performance, it is indicated that the TBDIMS design will provide greater sensitivity (fewer system losses) assuming that all other system characteristics such as laser power, optical efficiency, heterodyne efficiency are held constant.

3. DESIGN ANALYSIS

Several two-color β-system designs were analyzed to determine their performance characteristics. All the designs were found to reduce to two basic two-color β-system designs which will be analyzed in Sections 3.1 and 3.2.

A β-system which employs a beam splitter for combining the two transmitter output signals is analyzed in Section 3.1. A β-system which employs two folding insertion mirrors is analyzed in Section 3.2. As a system design trade-off between the two potential designs, a ray trace analysis which incorporates the effects of off-axis insertion of one of the input beams, is performed. The results of this analysis indicate that the signal to noise loss due to off-axis insertion of the second color is

less expensive, in terms of s/n loss, than the 50% beam splitter combining system which has 3 db of losses on the transmit leg and approximately 3 db of losses on the receiving leg of the system.

The dichroic beam splitter version of the BSCTCS has potential for an improved s/n performance over the 50% beam splitter version. Initial discussions [3] with vendors of such beam splitters indicate that as great as 80% transmission of 10.6 μm radiation can be achieved while at the same time reflecting as much as 80% of the 9.1 μm radiation. This performance will improve the BSCTCS design performance significantly both in the transmit leg and in the receiver leg, through use of separate L.O.'s. The transmitter and receiver leg loss are each reduced to less than 1 db.

3.1 DESIGN ANALYSIS OF THE BEAM SPLITTER COMBINED TWO-COLOR

Two options are presented with respect to beam splitter choices for this design. The first option employs conventional beam splitters, while the second option utilizes dichroic beam splitters, at critical points, in order to enhance the transmittance and reflectance at λ_1 and λ_2 as desired.

3.1.1 CONVENTIONAL BEAM SPLITTERS

Figure 3.1a gives the optical configuration for the beam splitter combined two-color β-system. This system combines the radiation from two CO_2 Lasers (λ_1 and λ_2) and passes the combined beam through a single interferometer. The output beam from Laser 1 is reflected off mirror M_1 and onto beam splitter S_1. The radiation from Laser 2 is reflected on beam splitter S_1 such that the output powers of the two lasers are combined at S_1 and are of approximately equal power. The requirement

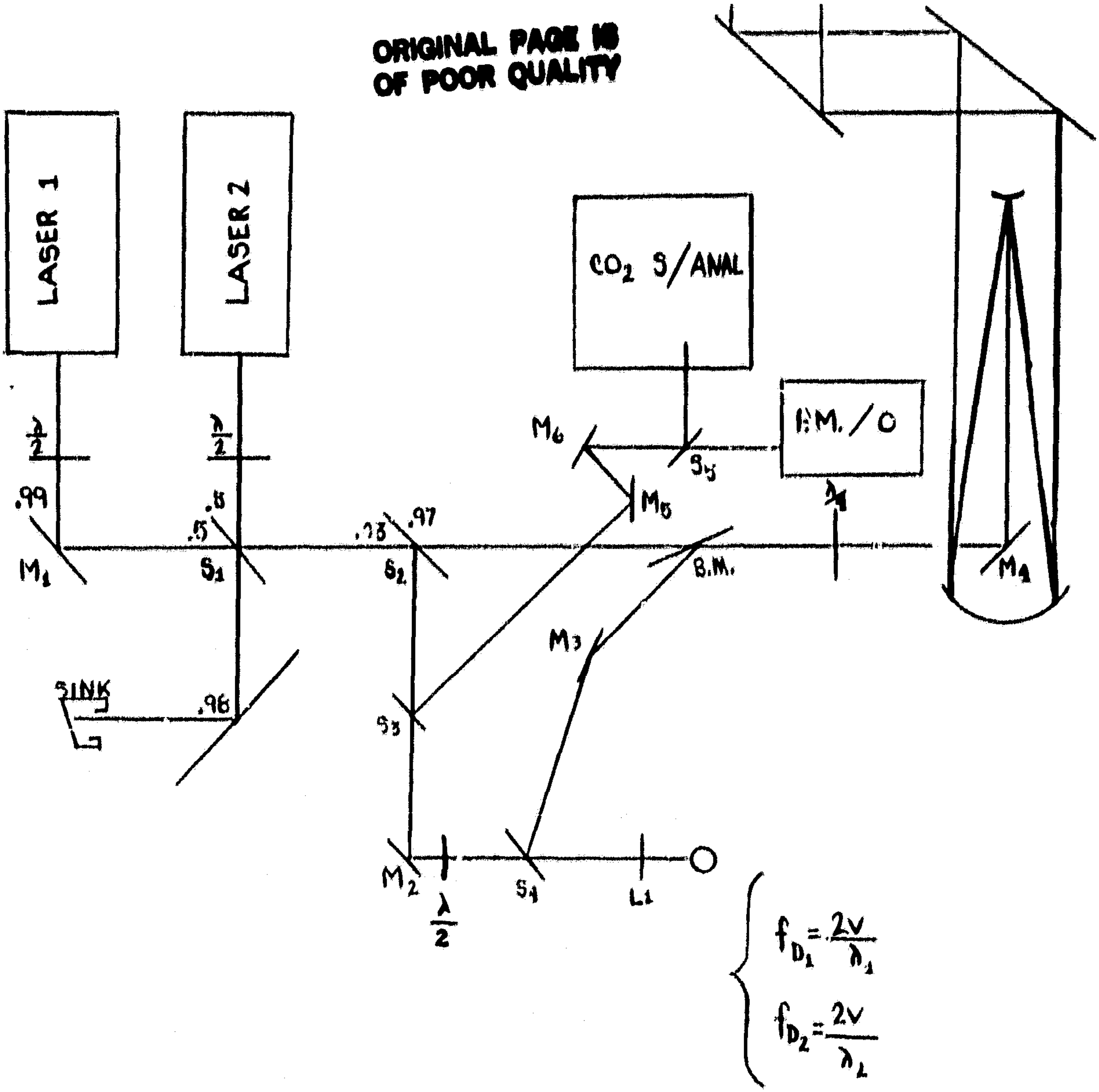

FIGURE 3.1a

TWO COLOR SYSTEM BEAM SPLITTER COMBINER DESIGN

*Necessary for vertically polarized lasers.

to have equal power components of λ_1 and λ_2 in the combined transmitted beam results in approximately 3 db of output power loss from each of the laser transmitters. The radiation that is reflected by S_1 must be dumped from Laser 1 and the radiation from Laser 2 that is transmitted by S_1 must be dumped from the system. Figure 3.1 shows this radiation being dumped into a radiation sink. The remainder of the system is exactly as the β-system which flew on the Ames Research Center's Convair 990 as part of MSFC Summer 1981 test program. (Reference Fig. 2, "Design and Calibration of a Coherent Lidar for Measurement of Atmospheric Backscatter", SPIE Conference, San Diego, CA, May 1981.) A positive attribute of this system is that the two colors are focused in the same spatial volume. This permits comparison of single particle signal returns for single particle measurement operations and a direct comparison of backscatter for the volume mode operation (without applying statistics to the signals).

This system may be operated in one of two possible modes for handling the signal processing of the reflected returns. The reflected radiation λ_1 and λ_2 may be heterodyned with the combined beams local oscillator signal which will result in the use of one detector and signal processor. The doppler returns when mixed with the combined λ_1 and λ_2 L. O. radiation can be sufficiently separated such that the signal processing of the separate colors will be possible. However, the L.O. radiation of λ_1 will appear as noise for the processing of λ_2 (reflected returns for λ_2) radiation against the L.O. and vice-versa for λ_1 and λ_2. This effect will tend to reduce the operating efficiency of this design further, maybe as much as 3 db.

This β-system design suffers from a system efficiency point of view in that the inherent losses for each color may be as much as 6 db, 3 db on the transmit leg and 3 db on the receiver leg.

3.1.2 DICHROIC BEAM SPLITTERS

A dichroic beam splitter can be designed[3] which will permit high reflectance at λ_2 and high transmittance at λ_1, or vice-versa. In Figure 3-1b such a splitter is utilized to effect separate mixing of λ_1 and λ_2 on separate detectors.

Transmit beams from Laser 1 and Laser 2 are combined at S_2, a dichoric splitter with strong transmittance at λ_1 and strong reflectance at λ_2. Local oscillator signals from Laser 1 and Laser 2 are not mixed, as in Figure 3-1a, but are combined separately with returned signals at S_4 and S_5, which are dichroic splitters with high reflectance for λ_1 and λ_2 respectively. It is only necessary to obtain enough L.O. upon transmittance to maintain shot noise limited operation. Also, the effect of strong reflectance of the λ_1 L.O. onto S_5 will be minimized since S_5 has strong λ_1 transmittance. This system offers about 2 db less power loss in transmit and receive legs than the previously discussed option.

3.2 DESIGN ANALYSIS OF THE β-SYSTEM EMPLOYING TWO BEAMS WITH FOCUSING AT SEPARATE POINTS

The schematic design of the two-beam system is shown in Figure 3.2. This design has inherently good optical efficiency in that it avoids the

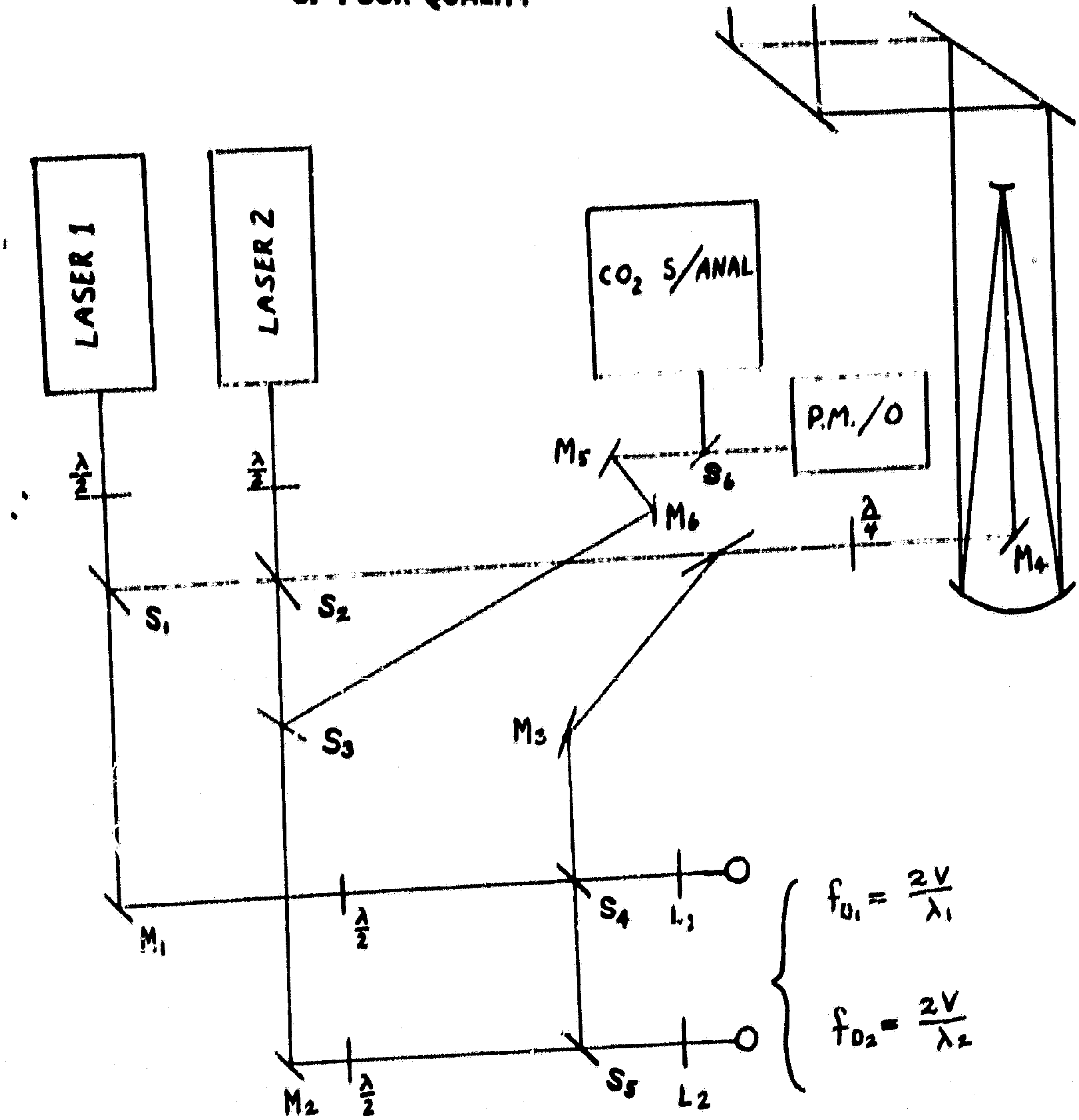

FIGURE 3.1b TWO COLOR SYSTEM (DICHROIC) BEAM SPLITTER COMBINER DESIGN

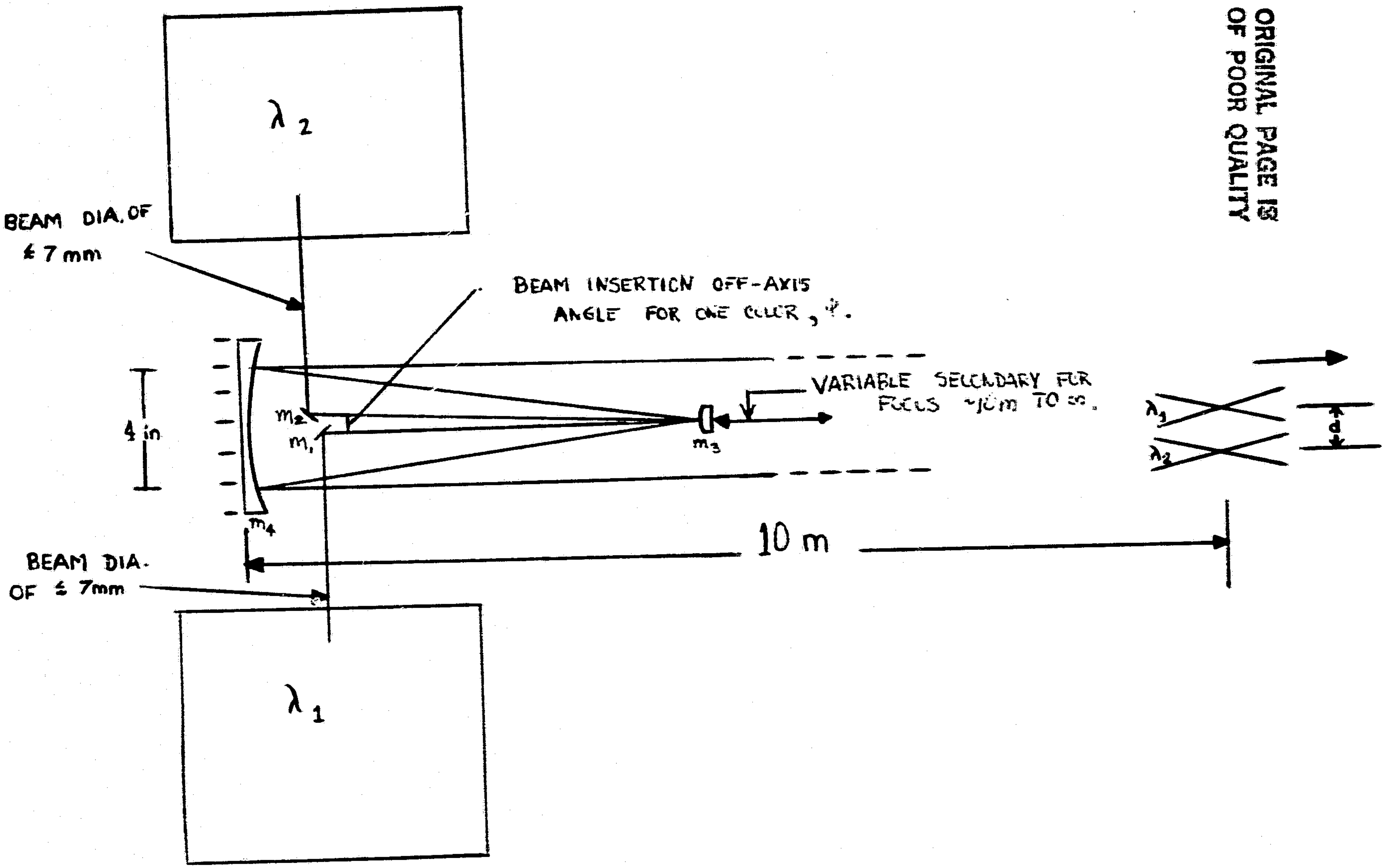

FIGURE 3.2

TWO COLOR BETA SYSTEM OFF-AXIS BEAM INSERTION DESIGN

previously discussed system's 3 db output power loss on the transmitter optical leg and avoids the $\sim$ 3 db signal loss in the receiver optical leg of the system. However, the potential for heterodyne efficiency degradation due to off-axis insertion of the λ_2 beam must be investigated to insure that the design's overall system efficiency is preserved. The following is a design analysis of the two beam directing insertion mirror system which considers the proposed optical design and employs the existing μ-system optical beam expanding telescope. Operating ranges of 10 meters and 30 meters have been considered in this analysis. It should be noted that focussing of this system at longer ranges tends to reduce the effect of off-axis beam insertion.

As depicted in Fig. 3.2 this optical design results in the two colors being focused at approximately the same range but in slightly separated spatial volumes.

A detailed discussion of this system's optical design and ray trace analysis is as follows.

One of the two flat mirrors, M_1 and M_2, shown in Figure 3.2, is located above the optic axis (out of the paper), with λ_1 parallel to the axis. The second λ_2 beam is located in the same plane (parallel to the paper) but displaced as shown. The plane of the two laser beams striking the secondary (small) mirror, M_3, is perpendicular to the plane of bilateral symmetry of the beam expander. The angle between the two beams is made as small as practicable to minimize aberation of the λ_2 beam.

The center of the λ_2 beam at the flat mirror is 1.3 cm from the plane of bilateral symmetry through the optic axis (perpendicular to the paper). The mirror is then adjusted so that both beams have spatially identical images on the large focusing mirror, M_4 (called the primary). These images are approximately 4 inches in diameter, as shown in Fig. 3.2. Note that the flat mirrors appear to obscure the beams coming from the secondary (see figure) but in fact do not, since the primary is completely off axis, in a direction out of the paper.

The center of the λ_1 beam strikes the secondary slightly above the optic axis (out of the paper). The center of the λ_2 beam strikes the secondary at the same distance above the optic axis and at a point that is displaced slightly in a perpendicular direction (toward the top of the paper). The amount of this lateral displacment of the point on the secondary is, however, less than 0.1 mm, and can easily be ignored in ray-tracing calculations. To see this, note that if the central ray of λ_2 struck the secondary at the same point as that of λ_1, it would be displaced at the primary by about 1.4 mm from the central ray of λ_1.

The Gaussian focal point (aberrations ignored) of the off-axis beam will be in the focal plane of the on-axis beam, and can be obtained by a simple geometrical construction. It is displaced to the opposite side of the optic axis from the plane mirror, and the displacement distance for the 10 meter focus is 0.3 inches.

By comparison of the wavefront shift at different points on the secondary in Table 3.9 and Table 3.10, we see that the two beams should have essentially the same characterisitcs. A second beam

added to the Lidar system, as described in this section, should give results almost as good as the original beam. Indeed, the differences between the two would be inconsequential.

3.2.1 ABERRATIONS OF THE TWO-BEAM SYSTEM

The geometrical theory of aberrations is given by many authors. The authoritative source Born and Wolf [1] (B & W) was used for the calculations reported here. This technique of evaluating an optical system is much more complete than other techniques that employ geometrical ray traces. The important performance characteristics of an optical system may be more adequately analyzed for the purpose of this design effort using the Born & Wolf approach. Most of the pertinent material is contained in Chapter V, pp 203-232. References to pages numbered 100 + are to pages in B and W. There are five third-order aberrations of a monochromatic system: Spherical aberration, astigmatism, curvature of field, distortion, and coma. Associated with these are five coefficients - B, C, D, E, and F, respectively - which can be calculated from the Gaussian variables (object distances, radii of curvature, image distances, etc.).

For a two mirror system like the beam expander considered here, the object distances are defined to be S_1 and S_2; image distances, S_1' and S_2'; and radii of curvature, r_1 and r_2. With the proper choice of signs for radii of curvature, (both positive) and indices of refraction ($n_o = 1$, $n_1 = -1$, $n_2 = 1$), one gets the following related quantities (p. 224):

$$
\begin{aligned}
h_1 &= -1 \\
h_2 &= -S_2/S_1' \\
k_1 &= 0 \\
k_2 &= d_1/h_2
\end{aligned}
$$

where d_1 is the distance between the primary and secondary mirrors. Four other quantities involved in the calculation of the aberration coefficients are

$$K_1 = \frac{1}{r_1} - \frac{1}{s_1}$$

$$K_2 = \frac{1}{s_2} - \frac{1}{r_2}$$

Eq. (15), p. 223

and $b_1 = -1 = b_2$. The values of b_1 and b_2, the deformation coefficients for the mirrors, represent the fact that the mirrors are paraboloidal.

It is convenient to define three more sets of intermediate variables

$$\alpha_i = \tfrac{1}{2} h_i^4 b_i (n_i - n_{i-1})/r_i^3$$

$$\beta_i = h_i^2 k_i K_i$$

$$\gamma_i = \tfrac{1}{2} (1/n_i s_i' - 1/n_{i-1} s_i').$$

The equations for the aberration coefficients (Eq. (24), p. 225) then become

$$B = \sum_i [\alpha_i + h_i^4 K_i^2 \gamma_i]$$

$$C = \sum_i [\alpha_i k_i^2 + (1 + \beta_i)^2 \gamma_i]$$

$$D = \sum_i [\alpha_i k_i^2 + \beta_i (2 + \beta_i) \gamma_i]$$

$$E = \sum_i [\alpha_i k_i^3 + k_i (1 + \beta_i) (2 + \beta_i) \gamma_i]$$

$$F = \sum_i [\alpha_i k_i + h_i^2 K_i (1 + \beta_i) \gamma_i]$$

The aberrations themselves are calculated using the so-called Seidel variables (pp. 208). For the purposes of this design analysis these are

$$y_0 = Y_0 / D_0$$

where Y_0 is the lateral displacement of the object point from the optic axis and D_0 is the object distance to the first mirror, and

$$\xi_2 = (X_2 + D_2 p_2)/M'$$

$$\eta_2 = (Y_2 + D_2 q_2)/M'$$

where (X_2, Y_2) is the lateral position of the image point, $(-D_2)$ is the image distance from the second mirror, and M' is the lateral magnification between the two mirror planes. The ray components p_2 and q_2 are direction cosines at the image plane (p. 134) with respect to the x and y axes, respectively, where the optic axis is the z axis.

The displacement of the wavefront (fourth-order correction) and displacement of the image point (third-order correction) are then calculated. Let $X_1 - X_1^*$ and $Y_1 - Y_1^*$ be the corrections to the position of the image point in the image plane (p.205).

Define ρ and θ by

$$\xi_2 = \rho \sin\theta \qquad \text{(p. 213)}$$

$$\eta_2 = \rho \cos\theta .$$

and define the displacement of the wavefront due to the aberrations as $\phi^{(4)}$. Then with

$$X_1 - X_1^* = \frac{D_2}{M'} \Delta^{(3)} x$$

$$Y_1 - Y_1^* = \frac{D_2}{M'} \Delta^{(3)} y$$

one finds (Eq. (7-8), p. 213)

$$\phi^{(4)} = \tfrac{1}{4} B\rho^4 - C\, y_0^2\, \rho^2 \cos^2\theta - \tfrac{1}{2} D y_0^2\, \rho^2 + E\, y_0^3\, \rho\cos\theta$$

$$+ F y_0\, \rho^3 \cos\theta$$

$$\Delta^{(3)} X = B\, \rho^3 \sin\theta - 2\, F y_0\, \rho^2 \sin\theta \cos\theta + D\, y_0^2\, \rho \sin\theta$$

$$\Delta^{(3)} y = B\, \rho^3 \cos\theta - F y_0\, \rho^2\ (1 + 2\cos^2\theta) + (2C + D)\, y_0^2\, \rho\cos\theta - E\, y_0^3$$

thus, there exists a complete method of calculating the aberrations once the Gaussian parameters are known.

3.2.2 BASIC PARAMETERS OF THE TWO-BEAM SYSTEM

The basic parameters needed for geometrical calculations are for the radii of curvature of the two mirrors and the distance between them. The basic data were given directly from the blueprint [2)] supplied by the original manufacturer of the beam expander. The most accurate data are the original distance between mirrors (for parallel beams) and the magnification which are respectively 32.670 and 14.987 inches. [Note: Henceforth, unless otherwise noted, all lengths are in inches. To avoid any round-off errors, more than the actual number of significant figures are given for some numbers.] The focal lengths are then determined to be

$$f_p \text{ (primary)} = 35.006$$
$$f_s \text{ (secondary)} = 2.3357$$

Most of the remaining parameters depend on the location of the image plane. The design effort considered examples where the image planes are 10 meters and 30 meters from the primary mirror. These are actually the focal planes of the two-mirror system.

3.2.3 ABERRATIONS IN THE FOCUS OF THE INITIAL LASER BEAMS

There are two basic problems to consider: (1) The aberrations in focussing the original beams and (2) the aberrations in the returning beams. The first case is considered in this section. The distances of the image plane (focal plane) from the primary (large) mirror are 10 meters (393.7 inches) and 30 meters (1811.1 inches).

The quantities needed for calculating the aberration coefficients (Section 3.2.1) are given in Table 3.1.

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Table 3.1

Quantities Needed for Calculating Aberration Coefficients

for 10 - meter and 30 - meter Focus

Quantity [a]	10 Meters [b]	30 Meters
r_1	4.6715	4.6715
r_2	70.012	70.012
d_1	36.087	33.740
s_1	$-\infty$	$-\infty$
s_1'	2.3357	2.3357
s_2	38.423	36.076
s_2'	393.7	1181.1
M'	16.46	15.44

a) See Section 3.2.1.

b) All lengths in inches.

From these quantities one can determine the related quantities h_1, k_i, K_i, α_i, β_i and the aberration coefficients (see Section 3.2.1). For the coefficients one gets the results in Table 3.2.

Table 3.2

Aberration Coefficients for Focus of Initial Laser Beams

Coefficient[a)]	10 Meters	30 Meters
B	-0.069152	-0.019091
C	-0.73171	-0.49090
D	-0.53193	-0.29112
E	1.3227	0.79201
F	0.15127	0.041664

a) See Section 3.2.1. The dimensions of the different coefficients are not uniform. Numbers given are in units of $(\text{inches})^n$ where n is an integer.

Rays to the image point can be identified in terms of points on the primary mirror from which they were reflected. This is the easiest way to determine the ray components p_2 and q_2, which are the direction cosines (Gaussian approximation) of the rays at the image plane. To encompass the beam, we pick points around the 4 inch spot made by the beam on the primary. Let the y - z plane be the plane of bilateral symmetry of the beam expander. We then label rays in terms of x and y positions on the primary mirror as follows:

	X Position	Y Position
Ray 1	5.80 inches	0
Ray 2	3.80 inches	2.00 inches
Ray 3	1.80 inches	0

These labels will be used in the calculations to follow.

The Seidel variables are calculated from the equations in Section 3.2.1. The angles of the rays are small enough that sines may be replaced by tangents to 3 significant figures. The image points for the λ_1 beam are, of course, on the optic axis. For the λ_2 beam, it is sufficient to find one ray through the image plane to locate the image point in the Gaussian approximation. The lateral magnification M' between the two mirror planes depends on d_1. Its values are given in Table 3.1. This means, of course, that the extent of the beam striking the primary varies slightly with image distance, by less than 7%. This variation has not been taken into account in choosing Rays 1 - 3, but fixed points on the primary have been used to define the rays, for simplicity.

For the λ_1 beam, we see that $y_o = 0$, so only B is involved in the aberrations (spherical aberration). For the λ_2 beam, y_o is the tangent of the angle made by a ray in the initial beam with the plane of bilateral symmetry of the beam expander. This involves the location of the flat mirror, which is taken as 3.00 inches forward of the primary, with the beam center striking the flat mirror at 1.3 cm from the symmetry plane. This gives

$$y_o = 1.31 \times 10^{-2}.$$

and for the positions of the Gaussian focal points of the beam,

$$(X_1^*, \; Y_1^*) = (0, -0.314) \text{ for 10 meters.}$$
$$= (0, -1.00) \text{ for 30 meters.}$$

Using these values, the Seidel variables ξ_2, η_2, ρ, $\sin\theta$, and $\cos\theta$, and from them the wavefront shifts $\psi^{(4)}$ and displacements $(X_1 - X_1^*, Y_1 - Y_1^*)$ can be calculated. The results for the λ_1 beam is given in Tables 3.3 - 3.4; those for the λ_2 beam are in Tables 3.5 - 3.6.

Table 3.3

Seidel Variables and Aberration

Results for On-Axis Beam; 10 - Meter Focus.

Quantity	Ray 1	Ray 2	Ray 3
[illegible]$_2$	0.352 [a)]	0.231	0.109
[illegible]$_2$	0	0.122	0
[illegible]$^{(4)}$	6.7 μm	2.0 μm	0.1 μm
$X_2-X_2^*$	- 0.072	-0.026	-0.002
$Y_2 - Y_2^*$	0	-0.014	0

a) All lengths in inches except as noted.

Table 3.4

Seidel Variables and Aberration

Results for On-Axis Beam, 30 - Meter Focus.

Quantity	Ray 1	Ray 2	Ray 3
ξ_2	0.376	0.246	0.117
$\eta_{2(4)}$	0	0.130	0
Φ	2.4 μm	0.7 μm	0.03 μm
$X_2 - X_2^*$	-0.078	-0.028	-0.002
$Y_2 - Y_2^*$	0	-0.015	0

Table 3.5

Seidel Variables and Aberration

Results for Off-Axis Beam; 10 - Meter Focus

Quantity	Ray 1	Ray 2	Ray 3
ξ_2	0.352	0.231	0.109
η_2	0	0.122	0
$\psi^{(4)}$	6.7 μm	2.6μm	0.008 μm
$X_2 - X_2^{\star}$	- 0.072	- 0.029	- 0.002
$Y_2 - Y_2^{\star}$	- 0.006	- 0.018	- 0.001

Table 3.6

Seidel Variables and Aberration

Results for Off-Axis Beam; 30 - Meter Focus

Quantity	Ray 1	Ray 2	Ray 3
ξ_2	0.376	0.246	0.117
η_2	0	0.130	0
$\Phi^{(4)}$	2.5 μm	1.0 μm	0.03 μm
$X_2 - X_2^*$	-0.079	-0.031	-0.003
$Y_2 - Y_2^*$	-0.006	-0.022	-0.001

The numbers in Tables 3.3 - 3.6 can be used to define the spot size of the focus in each case, as well as the wavefront variation for rays coming to different points on this spot. By comparing Table 3.3 with Table 3.5 and Table 3.4 with Table 3.6, it can be seen that the difference brought about by having the λ_2 beam offset from the symmetry plane is indeed slight. In regard to focussing properties, the two-beam β-system should perform essentially as well as the one-beam system.

3.2.4 ABERRATIONS IN THE RETURNING BEAMS

The question of the effect on waves reflected from the aerosol particles in the focus of a beam will now be considered. Again the cases of λ_1 and λ_2 beams at 10 and 30 meters are treated. The roles of primary and secondary mirrors are now reversed. Quantities corresponding to those in Table 3.1 are given in Table 3.7.

Table 3.7

Quantities Needed for Calculating

Aberration Coefficients for Returning Beams

Quantity	10 Meters	30 Meters
r_1	70.012	70.012
r_2	4.6715	4.6715
d_1	36.087	33.740
s_1	393.7	1181.1
s_1'	38.423	36.076
s_2	2.3357	2.3357
s_2'	$-\infty$	∞
M'	0.06075	0.06477

The related quantities are calculated as before, and we arrive at the aberration coefficients given in Table 3.8

Table 3.8

Aberration Coefficients for Returning Beams

Coefficient	10 Meters	30 Meters
B	9.4423×10^{-7}	3.3522×10^{-7}
C	-1.269×10^{-3}	-4.21×10^{-4}
D	-2.0105×10^{-1}	-2.0020×10^{-1}
E	-7.5126×10^{1}	-6.6612×10^{-1}
F	1.61×10^{-6}	1.7×10^{-7}

The parameter, $\phi^{(4)}$, the wavefront displacement at different points on the secondary mirror is calculated from

$$\xi_2 = X_2' \,/\, M'$$

$$\eta_2 = Y_2' \,/\, M'$$

where (X_2', Y_2') is the point at which a ray leaves the secondary. For simplicity Ray n' is defined as the reverse of ray n. Results are given in Tables 3.9 and 3.10.

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Table 3.9

Seidel Variables and Aberration

Results for Returning Beam on Axis

	Quantity	Ray 1'	Ray 2'	Ray 3'
10 meters	ξ_2	5.80	3.80	1.80
	η_2	0	2.00	0
	$\phi^{(4)}$	-6.8 μm	-2.0 μm	-0.06 μm
30 meters	ξ_2	5.80	3.80	1.80
	η_2	0	2.00	0
	$\phi^{(4)}$	-2.4 μm	-0.7 μm	-0.02 μm

Table 3.10

Seidel Variables and Aberration

Results for Returning Beams Off-Axis

	Quantity	Ray 1'	Ray 2'	Ray 3'
10 meters	ξ_2	5.80	3.80	1.80
	η_2	-1.51	2.47	-1.51
	$\phi^{(4)}$	-7.7 μm	-2.5 μm	-0.2 μm
30 meters	ξ_2	5.80	3.80	1.80
	η_2	-0.442	2.44	-0.442
	$\phi^{(4)}$	-2.4 μm	-0.08 μm	-0.02 μm

3.3 HETERODYNE EFFICIENCIES FOR THE ON-AXIS AND OFF-AXIS REFLECTED RADIATION: The heterodyne efficiencies associated with radiation backscattered into the system from λ_1 and λ_2 focal volumes can be calculated using the information contained in Table IX and X and Fig. 3.3. Figure 3.3 is taken directly from "Heterodyne detection: phase front alignment, beam spot size, and detector uniformity", Steven C. Cohen, August, 1975/ Vol. 14, No. 8/ Applied Optics, page 1957. The assumptions required for use of the Fig. 3.4 in calculating the heterodyning efficiency are as follows:

- o The local oscillator is assumed to have a Gaussian beam profile.
- o The returns signal beam profile is assumed to be an Airy Disk.
- o The Airy Received signal parameter X_o is given by $\frac{\pi r_o}{\lambda F}$ where r_o equal the detector radius $\underset{\sim}{\sim}$ .05 mm, λ equal the wavelength of the transmitted radiation, and F equal the F/No. for the focusing lens placed immediately in front of the detector. X_o is assumed equal to $\sim$ 3.
- o The Gaussian local oscillator parameter Z_o is given by $\frac{r_o}{w}$ where w = $\frac{1}{e}$ radius of L. O. beam. It is assumed that Z_o equals 1.

For a phase front tilt of λ over the detector the heterodyne detector parameter, $\dot{Y}$, is found to be $\sim$ 0.1. Note that, $Kr_o\theta = K\frac{\lambda}{2} = \frac{2\lambda}{\lambda}\ \frac{\lambda}{2} = \pi$ and from Fig. 3.3 (d) with Z_o = 1 and

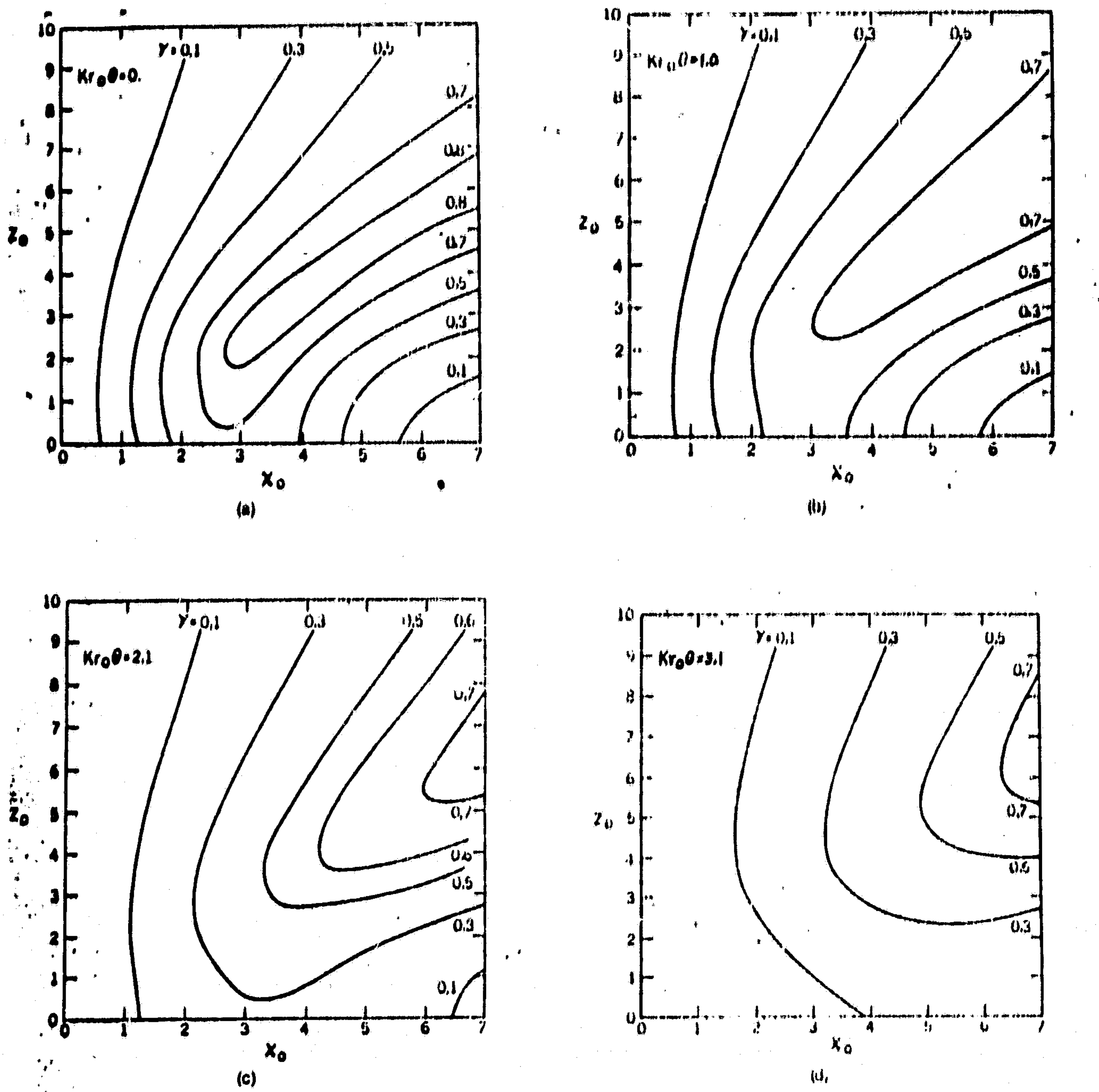
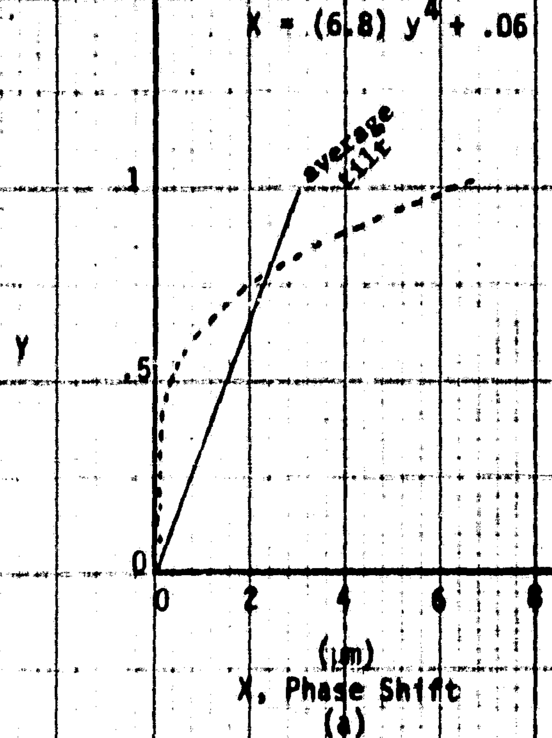


Figure 3.3. <u>HETERODYNE EFFICIENCY CONTOURS</u>

Contours of equal valued heterodyne detection parameter γ as a function of Airy received signal parameter X_o and Gaussian local oscillator parameter Z_o : (a) $Kr_o\theta = 0$; (b) $Kr_o\theta = 1$; (c) $Kr_o\theta = 2.1$; (d) $Kr_o\theta = 3.1$.



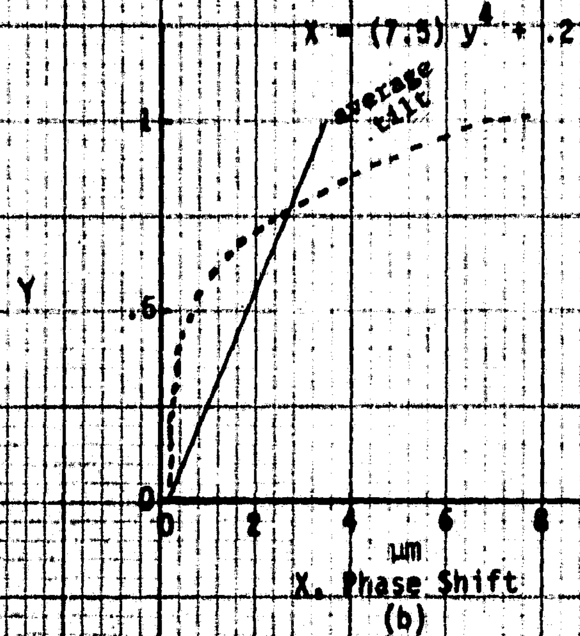


Figure 3.4
Approximation of Wave Front Tilt

$X_0 = 3$ it can be seen that $\gamma \simeq 0.1$. Similarly, for a wave front tilt of $\frac{\lambda}{2\pi}$ the γ is found to be ~ 0.6. Using the information from Fig. 3.3 and the phase shifts calculated for the proposed β-system in Tables IX and X the relative heterodyne detection parameter can be calculated.

From Table IX it can be seen that the phase shift for the two extreme rays, Ray $1'$ and Ray $3'$ (for the existing β-system) for returning beams on axis when the system is focused at 10 meters is approximately 6.7 μm. It is also understood that this tilt takes on a shape that is given by Fig. 3.4 (a). This fourth power relationship permits a conservative approximation of the wavefront tilt at the secondary to be estimated at ~ 1.5 μm. This is further supported by the assumed Gaussian beam shape on the local oscillator beam and the Airy disk beam shape on the reflected beam. An observation of Figure 3.3 indicates that the heterodyne detection parameter, γ, is approximately equal to 0.7.

This performance tends to increase as the existing system is focused at longer ranges and approaches $\gamma = 0.75$ for a focus at 30 meters. From Table X it can be seen that the phase shift for the two extreme rays, Ray $1'$ and Ray $3'$ (for the proposed β-system) for returning beams off-axis when the system is focused at 10 meters is approximately 7.5 μm. Again the tilt takes on a shape that is given by Fig. 3.4 (b).

This forth power relationship permits a conservative approximation of the wavefront tilt at the secondary to be estimated at 2.0 μm. This estimate is also supported by the assumed beam shapes

of the local oscillator and the reflected/collected beam. An observation of Figure 3.3 is that the heterodyne detection parameter, γ, is approximately equal to 0.65.

This performance tends to increase as the proposed system is focused at longer ranges and also approaches the $\gamma = 0.75$ for a focus at 30 meters.

4. SUMMARY

Currently completed analyses of the two basic two-color β-system designs which have been investigated, indicate that the two beam directing insertion mirror design will have the higher system performance efficiency, considering all other things equal. The study has resulted in a ray trace analysis which indicates that the existing system has a beam expanding telescope which couples with the Laser Doppler System to give relatively good heterodyne performance even when focused to 10 meters.

The ray trace analysis indicates that the system can accommodate off-axis beam insertion without the serious penalty of substantially lower heterodyne efficiency. Relative performance between the on-axis beam and the off-axis beam may be undetectable small when measured in the field.

The beam splitter combined two color β-system design has several desirable attributes in that it requires only one detector, interferometer, and signal processor thus potentially becoming a smaller and lighter instrument package. This design may potentially be the more desirable, of the two investigated designs, if performance efficiency for the system becomes less important and/or if simultaneous measurement of single particle signal events from λ_1 and λ_2 becomes more important. Further investigation and analysis of the data taken with the existing β-system will provide insight into the correct system design to choose for the two-color β-system.

1. Max Born and Emil Wolf, Principles of Optics, 4th. ed. (Pergamon Press, New York, 1970).

2. Blueprint supplied with Optronics International, Inc., beam expander, 15XC10150-VF.

3. T. Kordos, Broomer Laboratories, Inc. Plainview, N. Y., Personnel Communication.